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Centrifuge Modelling of Vertical Drains

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Introduction

Kjellman (1948), first introduced cardboard wick drain. Koerner (1994) illustrates the limitations of sand drain. Fabric packed sand drains are used successfully at Haneda project, Japan, (Kitazume et al., 1993) and at Wuhan district of China, (Feng and Hu, 1988). Fibre drain was used in Singapore, (Ramaswamy, 1992). Barron (1948) reported simplified expression for the design of vertical drains. Hansbo (1981) extended vertical drain theory to account for smear and well resistance effects.

Croce et al. (1988) investigated the validity of current theorise for vertical drain design using centrifuge at university of Colorado. However, they have not considered smear and well resistance effects, creep behaviour and natural soil fabric which have significant influence on field performance.

Feng and Hue (1988) reported that the settlements in soft soil foundation measured with the centrifugal model test agreed well with field measured settlements.

Lou and Gao (1988) studied the efficacy and mechanism of strengthening of soft soils with the vacuum preload and fill preload methods through centrifuge model tests.

Mandal and Shiv (1992) developed a design charts for the geocomposite vertical wick drain. Kitazume et al. (1993) investigated the effects of the geotextiles on stability and stress concentration by changing the tensile rigidity of the geotextile. Mandal and Joshi (1986) have extensively studied centrifuge modelling.

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The scheme of experiments is listed in the Table 1.

Table 1
Scheme of Experiments

Expt. No.	Model dia. cm.	Sample height cm.	Flow condition	Type of vertical drain	Drain diameter cm	w/c %	Ng level	Loading steps
1	5	5.7	V	—	—	80	120	4
2	5	5.7	R	SD	0.45	80	120	4
3	5	5.7	C	SD	0.45	80	120	4
4	5	5.7	C	SD	0.45	80	120	3
5	5	5.7	C	ESD	0.45	80	120	3
6	5	5.7	V	—	—	100	120	3
7	5	5.7	R	ESD	0.45	100	120	3
8	5	5.7	C	ESD	0.45	100	120	3
9	8	5.7	V	—	—	100	120	3
10	8	5.7	R	ESD	0.45	100	120	3
11	8	5.7	C	ESD	0.45	IQ0	120	3
12	5	5.7	C	ESD	0.60	100	120	3
13	8	5.7	C	ESD	0.60	100	120	3
14	5	4.5	C	ESD	0.45	100	120	3
15	8	4.5	C	ESD	0.45	100	120	3
16	5	5.7	C	JD	0.35	100	120	3
17	8	5.7	C	JD	0.35	100	120	3

where

V = vertical flow

R = radial flow

C = combined flow

SD = sand drain

ESD = encapsulated sand drain

JD = jute drains

N = acceleration level

w/c = water content

Four load steps are = 0.1 to 0.2, 0.2 to 0.5, 0.5 to 1.0, and 1.0 to 2.0 kPa

Three load steps are = 0.0 to 0.25, 0.25 to 0.75, and 0.75 to 2.0 kPa

Calculations

Optimum radius (R)

Optimum scaling radius is the radius upto 1/3 rd the height of the model from the centre of the centrifuge. The radius from the centre to the top surface of the basket is 31.5 cm and the thickness of the base plate is 1.2 cm, thus optimum scaling radius for a sample of H cm height is calculated as follows:

$$R = 31.5 - 1.2 - \frac{2}{3}(H)$$

Thus for the 5.7 cm height model,

$$R = 31.5 - 1.2 - \frac{2}{3}(5.7)$$

$$= 26.50 \text{ cm}$$

Speed of centrifuge

The speed of centrifuge is calculated as follows:

$$\omega^2 R = N \times g$$

$$\omega = \sqrt{\frac{N \times g}{R}}$$

$$\omega = 2\pi f$$

where f = frequency in cycles per second.

The speed of centrifuge in rpm, n_0, for 5.7 cm model and acceleration level 120 is given by

$$n_0 = \frac{60}{2\pi}\sqrt{\frac{N \times g}{R}}$$

$$n_0 = \frac{60}{2\pi}\sqrt{\frac{120 \times 981}{26.50}}$$

$$= 635 \text{ epm}$$

Load intensity

The details of load increments for four and three load steps are given in Tables 2 and 3 respectively.

Table 2
Details of Load Increments
(Four load steps)

Sr. No.	Field Stress kPa	Load Application gm
1	0.1 to 0.2	37.72
2	0.2 to 0.5	94.30
3	0.5 to 1.0	173.62
4	1.0 to 2.0	347.25

Table 3
Details of Load Increments
(Three load steps)

Sr. No	Field Stress kPa	Load Applied gm			
		N = 120		N = 150	
		dm = 5cm	dm = 8cm	dm = 5cm	dm = 8cm
1	0 0 to 0.25	43.55	111.54	33.87	86.66
2	0 25 to 0.75	132.16	337.65	104.34	267.10
3	0 75-2.0	355.80	915.14	288.35	738.20

where n = scale factor and

dm = model container diameter.

Preparation of Soil

A set of laboratory experiments to determine the index properties of the soil have been conducted as per IS code specifications and results are summarized in Table 4.

Table 4
Summary of Index Properties of Soil

Type of soil	Bombay Marine Clay
Particle size	Passing through 42511 sieve
Specific gravity	2.65
Liquid limit	78%
Plastic limit	38%
Plasticity index	40
Shrinkage limit	17.30%

1. Soil (Bombay marine clay) passing through 425 μm IS sieve (BS 36) is first made oven dry by placing the soil in an electric oven for 24 hours.

2. Soil from the oven is then allowed to cool in a dessicator.

3. Required quantity of the soil is taken from the dessicator and weighed accurately in a mechanical balance.

4. Calculated quantity of distilled water is then added to the soil.

5. Soil is first mixed by hand with a spatula to break lumps and then mixed thoroughly with an electric mixer to make a homogeneous slurry.

6. Soil slurry thus prepared is then immediately checked for water content by placing two samples in a microwave oven which dries the sample completely in six minutes. The soil is now ready to be transferred into the container.

Preparation for Encapsulated Drains

The non woven needle punched geotextile pipe is filled with sand and then saturated. Saturation of sand pipe doesn't allow sand particles to fall out of encapsulation at the time of installation. The encapsulated sand drain is ready to be lowered. Specifications of encapsulated sand drain which are kept constant throughout the experiment is given in Table 5.

Table 5
Details of Encapsulated Sand Drain

Description	Weight (gm)	
	dwm = 4.5 mm	dwm = 6.0 mm
Weight of geotextile pipe	0.06	0.05
Weight of geotextile + dry sand	1.40	2.43
Weight of geotextile + dry sand.	1.95	3.41

where dwm is encapsulated sand drain diameter;
length of fabric-pack is 65 mm.

Preparation of Model

1. The cylindrical container is first washed thoroughly with soap and water and then dried with cotton waste.

2. Silicon grease is then applied on the inside wall of the container with a wooden rod with rubber wound around at one end to eliminate the frictional resistance.

3. A steel pipe of inner diameter 7.2 mm, outer diameter 8.24 mm and length of 10 cm is used as casing. Thin layer of grease is applied to the outer surface of steel casing to minimise the smear effect while taking out the casing. The drain is lowered exactly at the enter of model base.

4. The slurry prepared is then transferred into the container, layer by layer till the required height of the sample is reached. For each layer, slurry is transferred into the container with spatula. Proper care is taken to avoid blockage of air bubbles.

5. The casing is taken out gently.

6. A filter paper having hole at centre is then placed at the top of the sample.

7. Perspex plate as per the condition of drainage is placed on the top of the filter paper. One more filter paper is provided on the top of perspex plate.

8. The transducer is then fixed to the container with a clamp such that the shaft of transducer rests on rigid surface of perspex plate.

9. Calculated quantity of sand/lead shots is then placed over the piston as per the load calculation.

Procedure of Experiments

1. The soil model container is exactly counter balanced with other weights (other container + sand + lead shots)

2. The soil model container and the counter weight are properly placed into the respective centrifuge basket.

3. Data logger and transducer assembly are fixed in centrifuge.

4. Centrifuge cover is then placed in its position such that the window is exactly on the diametrically opposite side of the proximity switch.

5. The current is switched on, the centrifuge is set to run at the desired acceleration level.

6. After an experiment is over, the data logger is taken out and connected to the computer to off load the data.

7. Before the load for next step the excess water is drained out.

8. After the experiment is over, water contents at top, middle and bottom of soil sample are measured.

Verification of Sand Drain Consolidation Theories

Three centrifuge tests, are conducted with the flow conditions only vertical, only radial and combined flow as shown in Fig. l. Experiments are conducted at 120g acceleration. Soil sample is prepared by adding 80% water content. The centrifuge results for three flow conditions are recorded for the cases vertical, radial and combined flow conditions. The time against settlement curves are shown in Fig.s 2a to 2d and time against degree of settlements are shown in Fig.s 3a to 3d for four loading steps. Here Dp is prototype influence diameter, dwp is prototype drain well diameter, wc is water content and N is scale factor. Theoretical results of time and degree of settlement for similar prototype are obtained by using relevant theoretical analysis.

The comparison between theoretical and centrifuge results for vertical flow condition are shown in Fig.s 4a to 4d foil four loading steps. It is

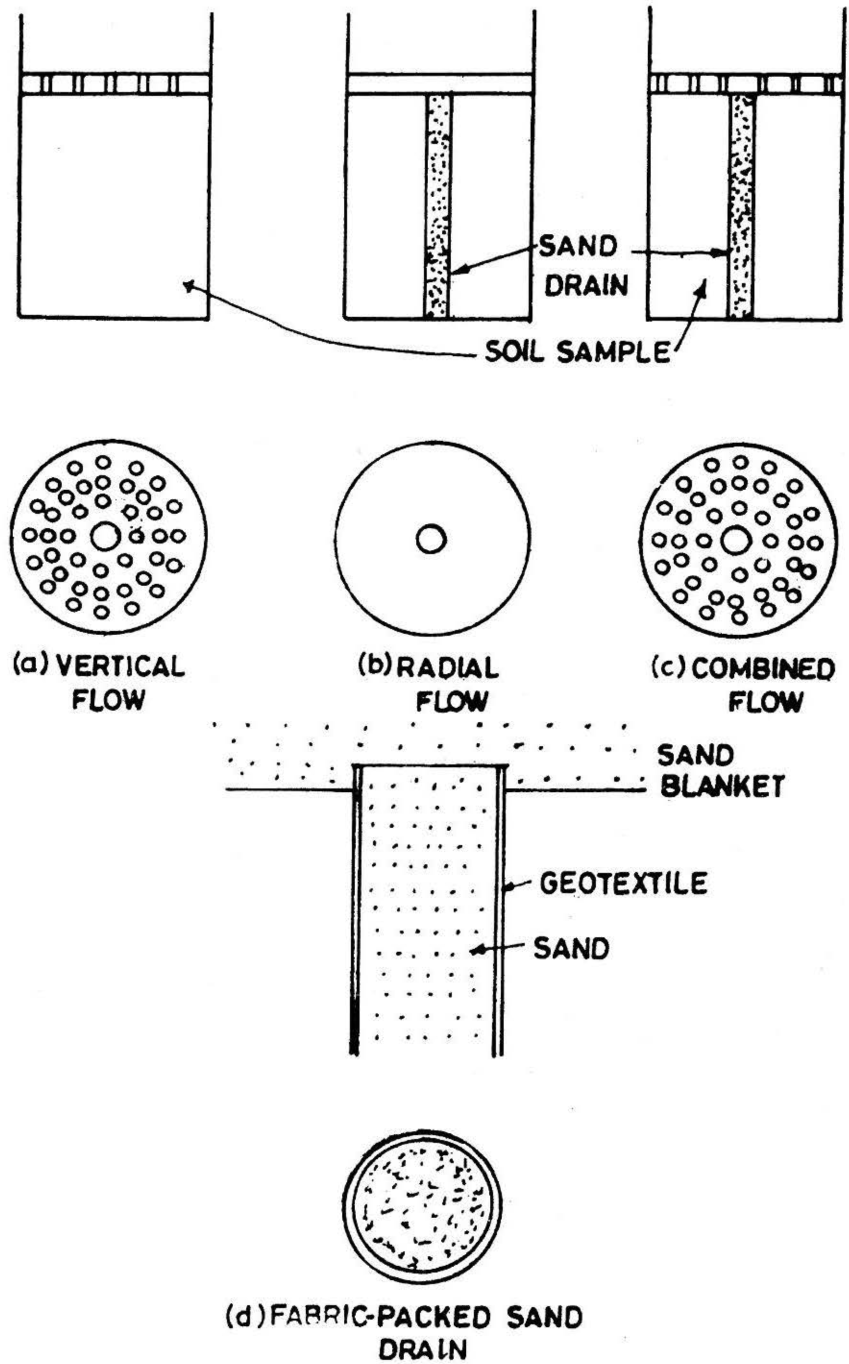

FIGURE 1 : Model Container

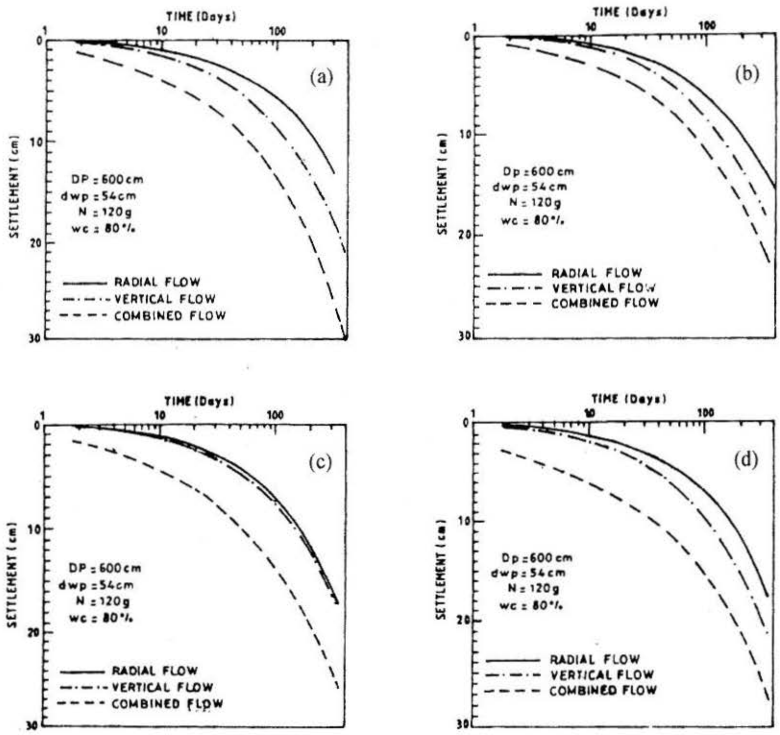

FIGURE 2 : Time – Settlement Curves of Vertical Sand Drain (Radial and Combined Flow) and Marine Clay (Vertical Flow) using Centrifuge Modelling for (a) 0.1 to 0.2 kPa, (b) 0.2 to 0.5 kPa, (c) 0.5 to 1.0 kPa, (d) 1.0 to 2.0 kPa Loading

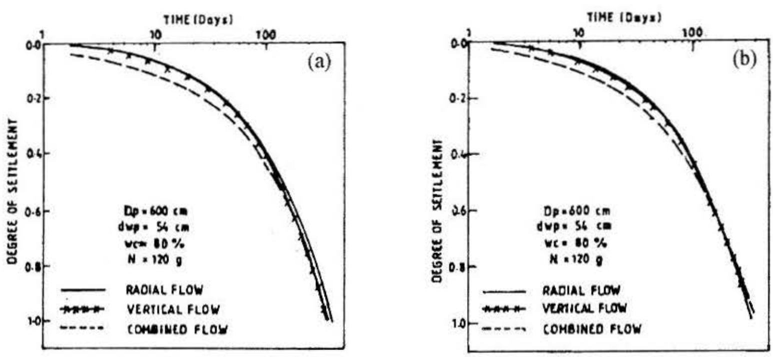

FIGURE 3 : Time – Degree of Settlement Curves of Vertical Sand Drain (Radial and Combined Flow) and Marine Clay (Vertical Flow) using Centrifuge Modelling for (a) 0.1 to 0.2 kPa, (b) 0.2 to 0.5 kPa

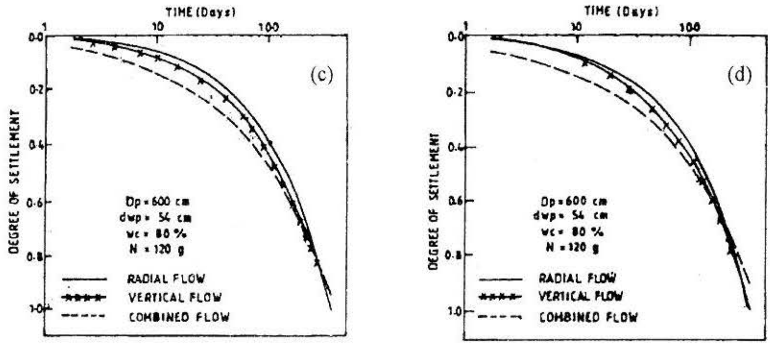

FIGURE 3 (contd.) : Time – Degree of Settlement Curves of Vertical Sand Drain (Radial and Combined Flow) and Marine Clay (Vertical Flow) using Centrifuge Modelling for (c) 0.5 to 1.0 kPa, (d) 1.0 to 2.0 kPa Loading

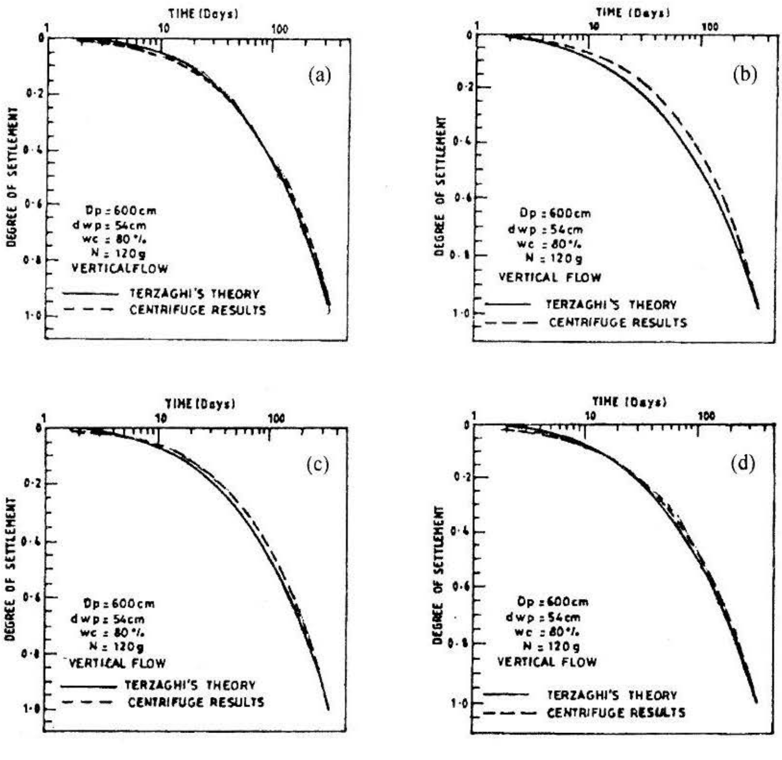

FIGURE 4 : Time – Degree of Settlement Curves of Marine Clay (Theoretical and Experimental) using Centrifuge Modelling under the Loading (a) 0.1 to 0.2 kPa, (b) 0.2 to 0.5 kPa, (c) 0.5 to 1.0 kPa, (d) 1.0 to 2.0 kPa for Vertical Flow Condition

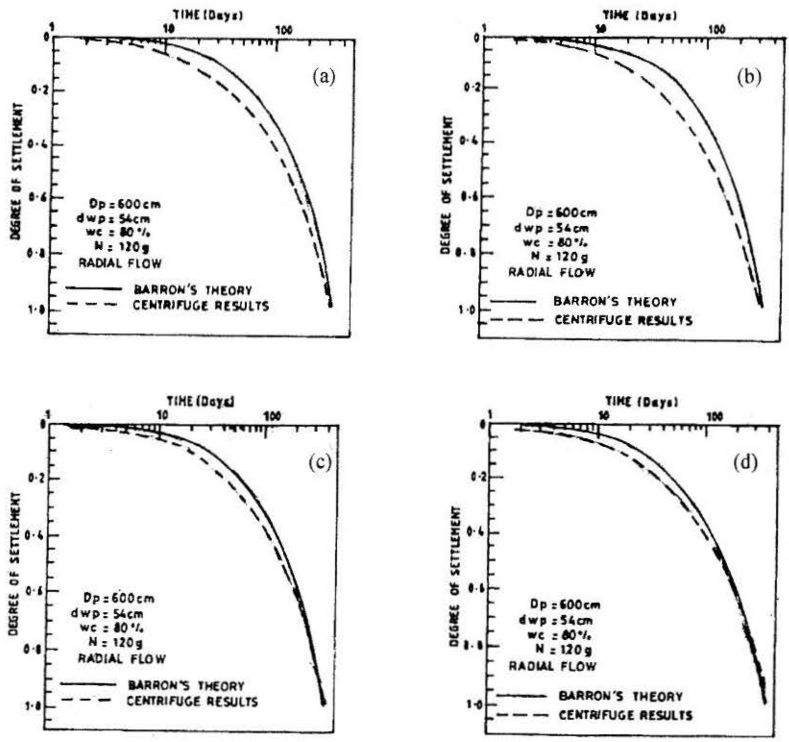

FIGURE 5 : Time – Degree of Settlement Curves of Marine Clay (Theoretical and Experimental) using Centrifuge Modelling under the Loading (a) 0.1 to 0.2 kPa, (b) 0.2 to 0.5 kPa, (c) 0.5 to 1.0 kPa, (d) 1.0 to 2.0 kPa for Radial Flow Condition

consistently observed that measured settlements are faster than predicted by Terzaghi's theory (1923) in the initial stages. But latter on settlements calculated by theory are more than the measured settlements. It has also been observed that, at the end of experiment both curves converge. The difference in the settlements for both the cases is small.

Similarly, the degree of settlement measured by radial flow model tests compared with Barron's equal strain theory (1948) are shown in Fig.s 5a to 5d for four loading steps. In this case also, very good agreement is observed between the theoretical and experimental results. The measured settlements are always found faster than theoretical results. The convergence of both curves are observed at the end of experiments. The difference in settlement at any time in both cases is negligible.

The results of combined flow tests, which completely simulate the prototype boundary drainage conditions, is compared with the results obtained

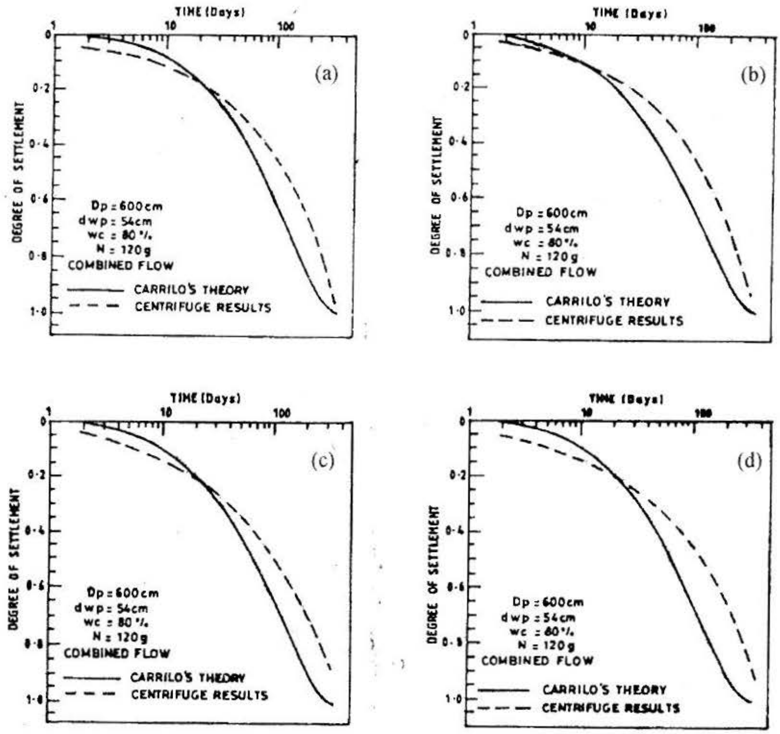

FIGURE 6 : Time – Degree of Settlement Curves of Marine Clay (Theoretical and Experimental) using Centrifuge Modelling under the Loading (a) 0.1 to 0.2 kPa, (b) 0.2 to 0.5 kPa, (c) 0.5 to 1.0 kPa, (d) 1.0 to 2.0 kPa for Combined Flow Condition

by linear combination of Terzaghi's theory (1923) and Barron's theory (1948) as suggested by Carrilo (1935) as shown in Fig.s 6a to 6d for four loading steps. It is observed that the rate of settlement computed by Carrilo's theory is slower than measured rate of settlement at the initial stages but is consistently faster after three minutes. In this case also observed differences in settlements are small between experimental and theoretical cases and both curves converge at the end of experiment.

The small geotechnical centrifuge in which experiments were conducted can not be run continuously for longer time. Hence, taking this limitation into account subsequent experiments were conducted for three loading steps.

Centrifuge Study for Encapsulated Sand Drains

Two combined flow experiments are conducted, one with sand drain and other with encapsulated sand drain. Model is prepared at 1:120 scale.

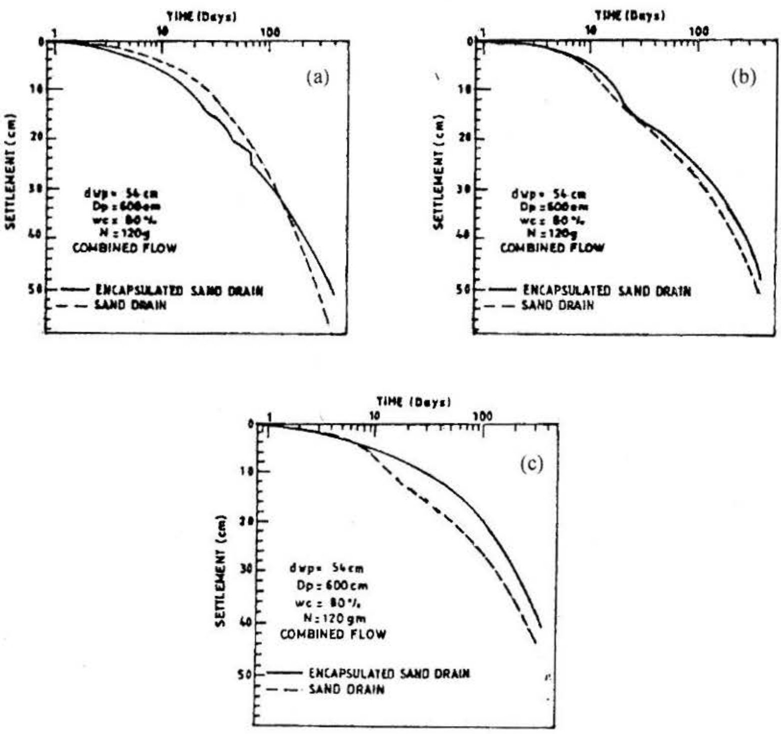

FIGURE 7 : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

Soil sample is prepared by adding 80% water. Time against settlement curves for both case are plotted in Fig.s 7a to 7c for three loading steps.

It has been observed with series of experiments at two moisture contents 80% and 100%, that the sand drain couldn't stand by itself for moisture content more than 90%. The observed rate of settlement for encapsulated sand drain is slower than sand drain. This is because of well resistance effect of encapsulation. The rates of settlement curves follow same path in both the cases.

Effect of Flow Conditions on Settlements

Total six number of experiments are conducted for three flow conditions viz., vertical, radial and combined with 5cm and 8cm diameter mold. The model is prepared at 1:120 scale. Water content of soil sample was 100%. The sand drain is reinforced with non-woven geotextiles. Time against

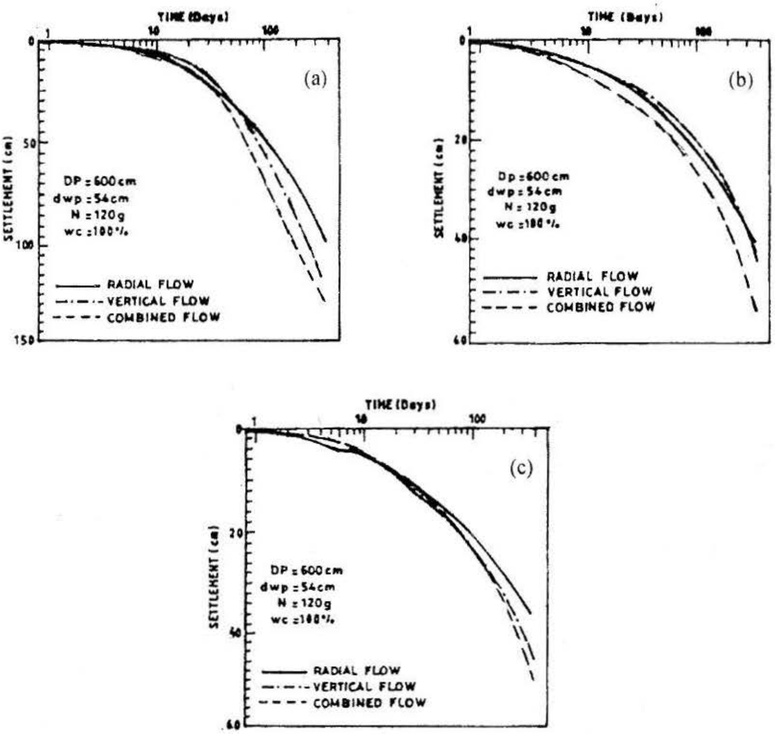

FIGURE 8 : Time – Settlement Curves of Encapsulated Sand Drain (Radial and Combined Flow) and Marine Clay (Vertical Flow) using Centrifuge Modelling under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

settlement curves are shown in Fig.s 8a to 8c for 600 cm influence diameter and Fig.s 9a to 9c for 960 cm influence diameter under three loading steps.

It is observed that 6.85 m thick marine clay with 100% moisture content couldn't bear load more than 0.30 kpa. Maximum settlements are observed for combined flow condition as compared to radial and vertical flow conditions. It is also observed that rate of settlement for vertical flow condition is faster than radial flow condition. Water content measured after the experiment for combined flow found much less than other flow conditions. In the case of 8 cm diameter mould and radial flow case, less water content was observed at a section close to the drain well.

Study of Ratio of Influence Diameter to Drain Diameter

Centrifuge tests are conducted with encapsulated sand drain diameter 54 cm and 72 cm and influence diameter 600 cm and 960 cm. In this case

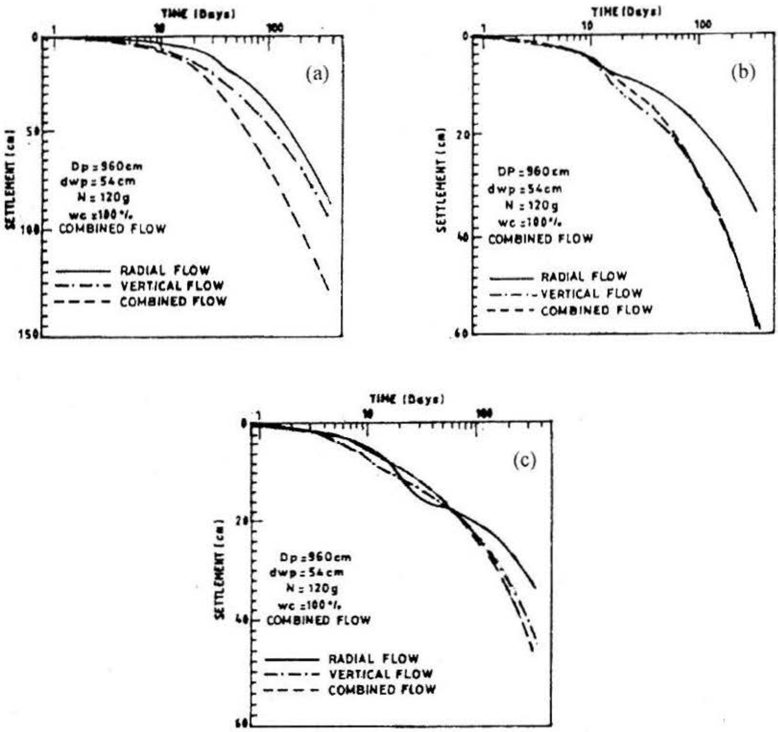

FIGURE 9 : Time – Settlement Curves of Encapsulated Sand Drain (Radial and Combined Flow) and Marine Clay (Vertical Flow) using Centrifuge Modelling under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

only combined flow condition is considered. Water content of soil sample was 100%. The model is prepared at 1:120 scale. Here 'n' is the ratio of influence diameter (D) to drain well diameter (dw), (n = D/dw).

Figures 10a to 10c compare the settlements for the case in which the model drain well diameter (dpw = 54 cm) was kept constant whereas the prototype influence diameters Dp, were 600 cm and 960 cm for three loading steps.

From Fig.s 10a to 10c it is observed that, for n = 11.11 the rate of settlement is consistently faster than n = 17.78, for all the three load steps. The drainage path is shorter in 600 cm influence diameter than 960 cm influence diameter. From Fig.s 11a to 11c for three loading steps it is observed that the rate of settlement for n = 8.33 is faster than n = 11.11.

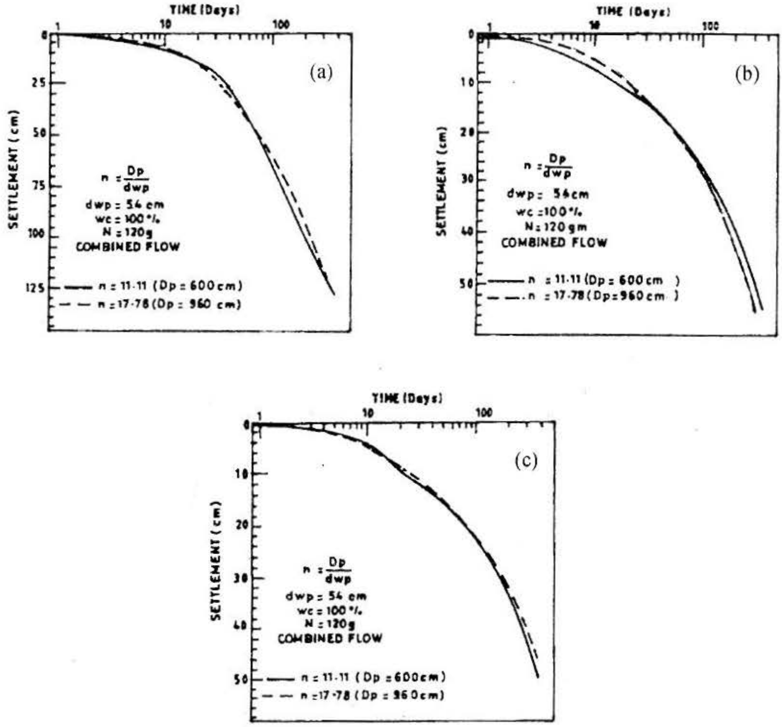

FIGURE 10 : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain for Various Ratios of Influence Diameter to Drain Diameter (n = 11.11 and n = 17.78) under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

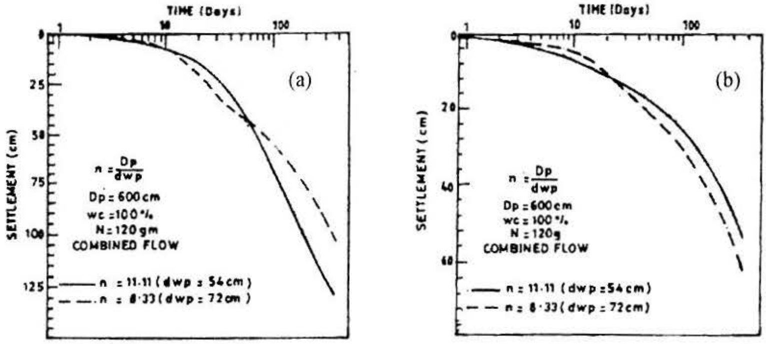

FIGURE 11 : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain for Various Ratios of Influence Diameter to Drain Diameter (n = 11.11 and n = 8.33) under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa

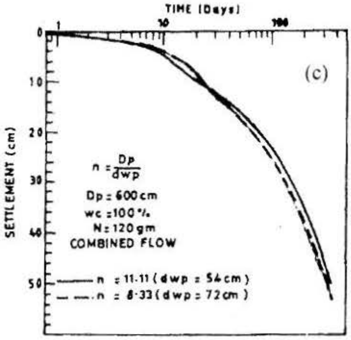

FIGURE 11 (contd.) : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain for Various Ratios of Influence Diameter to Drain Diameter (n = 11.11 and n = 8.33) under the Loading (c) 0.75 to 2.0 kPa

Study of Different Acceleration Levels

A prototype marine clay of depth 6.85 m is modelled at an acceleration level, N, conducted with model container diameter Dm, equal to 5 cm and 8 cm with encapsulated sand drain. The time against settlement results are plotted as shown in Fig.s 12a to 12c for influence diameter 600 cm and Fig.s 13a to 13c for three loading steps. The observed rate of settlement is faster for N = 120 than N = 150. This might be because of more depth of soil sample at low acceleration. More study is required to decide the optimum acceleration.

Centrifuge Study of Jute Rope Drain

Two centrifuge experiments are conducted with jute rope as a vertical drain. The model is prepared at 1:120 scale. The water content of soil slurry was 100%. The jute rope of diameter 3.5 mm is installed as a vertical drain. Time settlement curves are plotted as shown in Fig.s 14a to 14c for three loading steps. The jute rope drain results are compared with the corresponding encapsulated sand drain results as shown in Fig.s 15a to 15c for influence diameter 600 cm and Fig.s 16a to 16c for 960 cm influence diameter for three loading steps.

It is observed that, the rate of settlement follows a path similar to that observed in sand drain and encapsulated sand drain. The rate of settlement is consistently faster in jute rope drain for prototype influence diameters 600 cm and 960 cm. The observed settlements for jute rope drain diameter of 42 cm are faster than encapsulated sand drain of diameter of 54 cm.

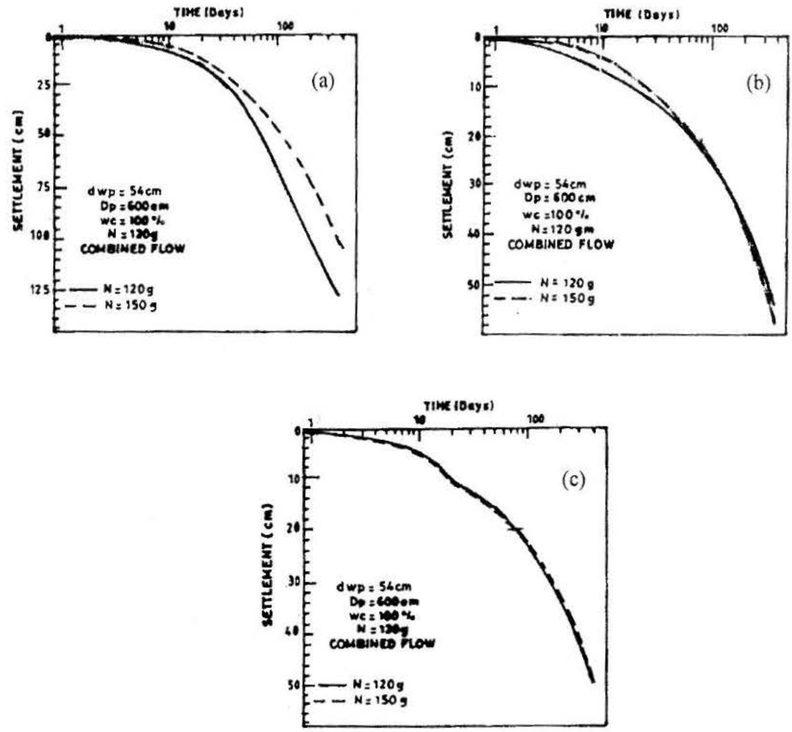

FIGURE 12 : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain for Various Accelerations (N = 120g and N = 150g) under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

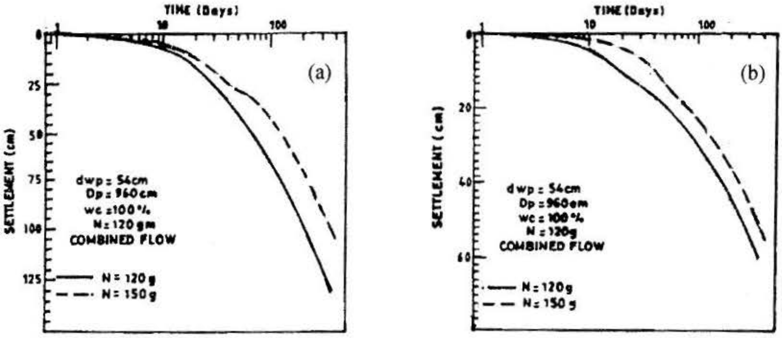

FIGURE 13 : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain for Various Accelerations (N = 120g and N = 150g) under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa

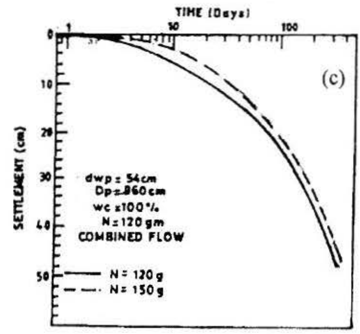

FIGURE 13 (contd.) : Centrifuge Time – Settlement Curves of Encapsulated Sand Drain for Various Accelerations (N = 120g and N = 150g) under the Loading (c) 0.75 to 2.0 kPa

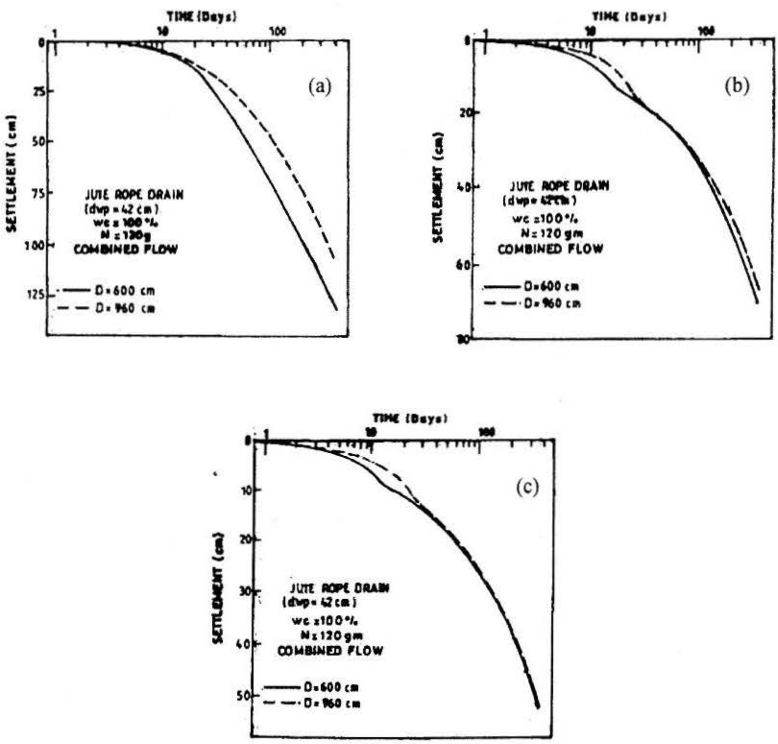

FIGURE 14 : Centrifuge Time – Settlement Curves of Jute Rope Drain for Different Influence Diameter (D = 600cm and D = 960cm) under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

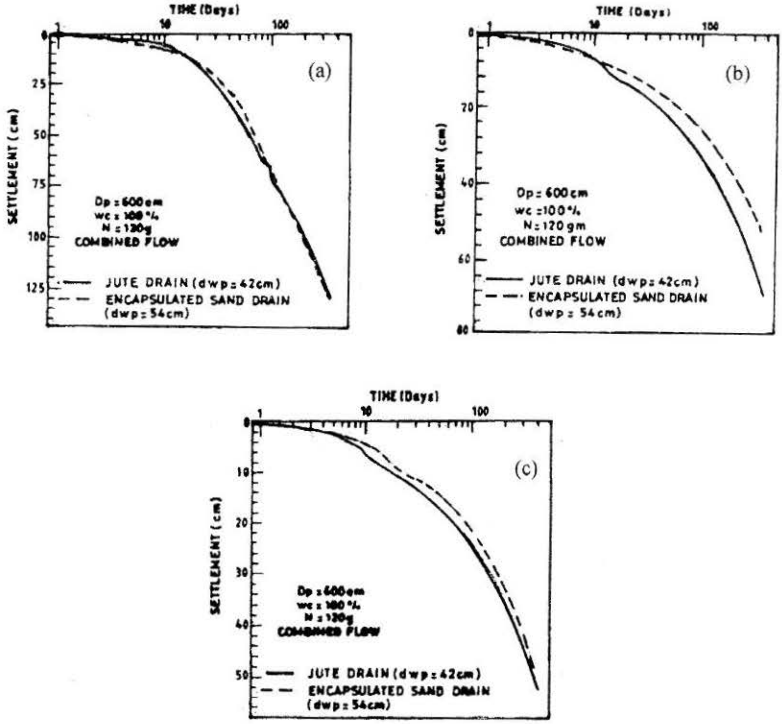

FIGURE 15 : Comparison of Centrifuge Time – Settlement Curves of Jute Rope Drain of Diameter 42cm and Encapsulated Sand Drain of Diameter 54cm under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

Conclusions

A series of centrifuge model tests of vertical drain in Bombay marine clay have been conducted and following conclusions are made :

1. The consolidation theories viz. vertical flow (Terzaghi), radial flow (Barron) and combined flow (Carrilo) are in close agreement with centrifuge results in sand drain case.

2. Encapsulation of sand drain is required, when moisture content of marine clay is more than 90%.

3. The prototype field condition such as depth of marine clay 6.85 m and water content 100%. would not bear load more than 0.30 kPa.

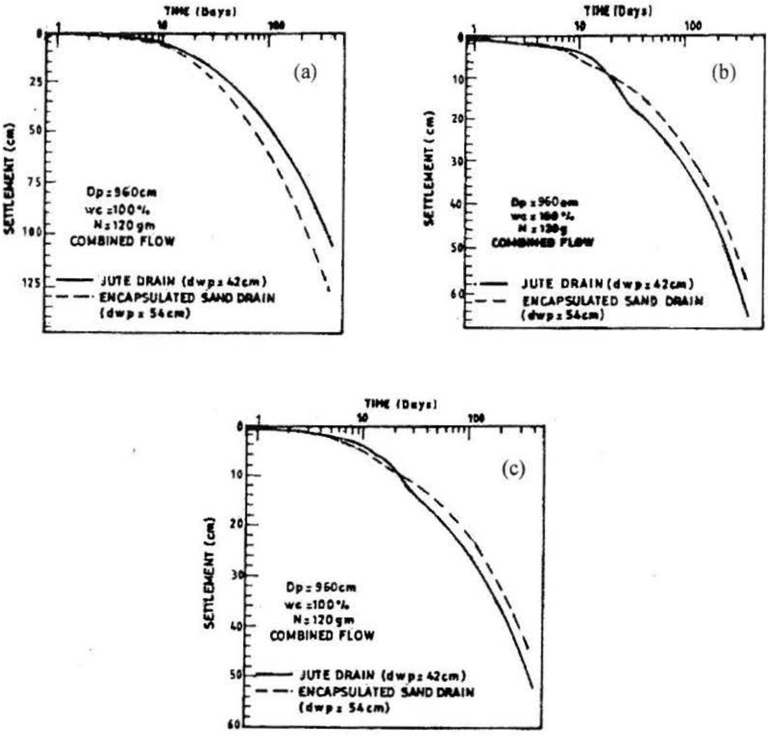

FIGURE 16 : Comparison of Centrifuge Time – Settlement Curves of Jute Rope Drain of Diameter 42cm and Encapsulated Sand Drain of Diameter 54cm under the Loading (a) 0 to 0.25 kPa, (b) 0.25 to 0.75 kPa, (c) 0.75 to 2.0 kPa

4. The rate of settlement is same in both sand drain and encapsulated sand drain cases. The higher well resistance effect is observed in the case of encapsulated sand drain.

5. Smaller 'n' (ratio of influence diameter to drain diameter) values are effective to achieve higher degrees of consolidation in short time.

6. The rate of settlement reduces for higher acceleration level. It is suggested, more detail experimentation required to decide the optimum acceleration level.

7. The water content in 8 cm mould diameter in radial flow case, was predominantly less in a soil section close to sand drain.

8. Jute rope drain of 42 cm diameter is more efficient than an encapsulated sand drain of 54 cm diameter.

Acknowledgement

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References

BARRON, R.A. (1948) : "Consolidation of Fine Grained Soils by Drain Wells", *ASCE Transactions*, Paper no. 2346, pp.716-753.

CROCE, P., KO, H.Y., SCHIFFMAN, R.L. and ZNIDARCIC D. (1988) : "The Influence of Vertical Drains on Consolidation", A.A. Balkema, *Centrifuge-88*, pp.171-180.

FENG, G. and HU, Y. (1988) : "Centrifuge Model Test of a Highway Embankment on Soft Clay", A.A. Balkema, *Centrifuge-88*, pp.153-159.

HANSBO, S. (1981) : "Consolidation of Fine Grained Soils by Prefabricated Drains", *X Int. Conference on SMFE*, Stockholm, pp.677-682.

KITAZUNE, M., TERASHI, M. and AIHARA, N. (1993) : "Centrifuge Model Tests on the Consolidation Behaviour of Soft Clay with Fabric Packed Sand Drains", *Geosynthetics-93*, Vancover, Canada, pp.393-408.

KJELLMAN, W. (1948) : "Accelerating Consolidation using Sandwick", *2nd Int. Conference, SMFE*, Vol.2, pp.302-305.

KOERNER, R.M. (1994) : *Designing with Geosynthetics*, Third Edition, Prentice Hall Englewood. New Jersey.

LOW, L. and GEO, Y. (1988) : "Experimental Study on Consolidation of Soft Soils under Negative Pressure with Centrifugal Models", *Centrifuge-88*, pp.181-184.

MANDAL, J.N. and SHIV, A. (1992) : "CAD of Geocomposite Vertical Strip Drains", *Construction and Building Materials*, Vol.6, No.4, pp.219-225.

MANDAL, J.N. and JOSHI, A. A. (1996) : "Centrifuge Modelling of Geosynthetics Reinforced Embankments on Soft Ground", *Geotextiles and Geomembranes*, Elsevier Applied Science, Vol.14, No.2, pp.147-155.

RAMASWAMY, S.D. (1994) : "Potential of Jute Assembled Soil Stabilisers", *Proc. 2nd Int. Workshop on Geotextiles*, New Delhi, pp.77-85.

Errata

IGJ, Vol.27, No.2, April 1997, p.158

Read $T = \sqrt[4]{\frac{EI}{k_h}} = \sqrt[4]{\frac{2.18 \times 10^5 \times 187 \times 10^4}{0.837}} = 835 \text{ mm}$

instead of $T = \sqrt[4]{\frac{EI}{kh}} = \sqrt{\frac{2.18 \times 10^5 \times 187 \times 10^4}{0.837}} = 835 \text{ mm}$